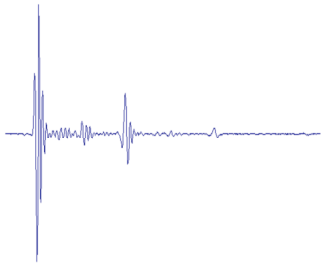
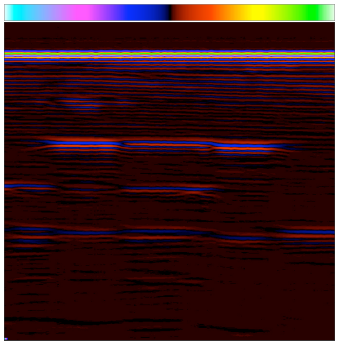
UCRL-PRES-208121
Signal and Imaging Sciences Workshop, Center for Advanced Signal and Imaging Sciences, Lawrence Livermore National Laboratory, November 18-19, 2004

Impulse Response Estimation for Spatial Resolution Enhancement in 3D Ultrasonic Nondestructive Evaluation Imagery



Grace A. Clark (EE/EETD)
Steven E. Benson (ME/MMED)

November 19, 2004



This work was performed under the auspices of the U.S. Department of Energy by the University of California, Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

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Go Boilers!!!

Purdue's "All-American" Marching Band

Agenda

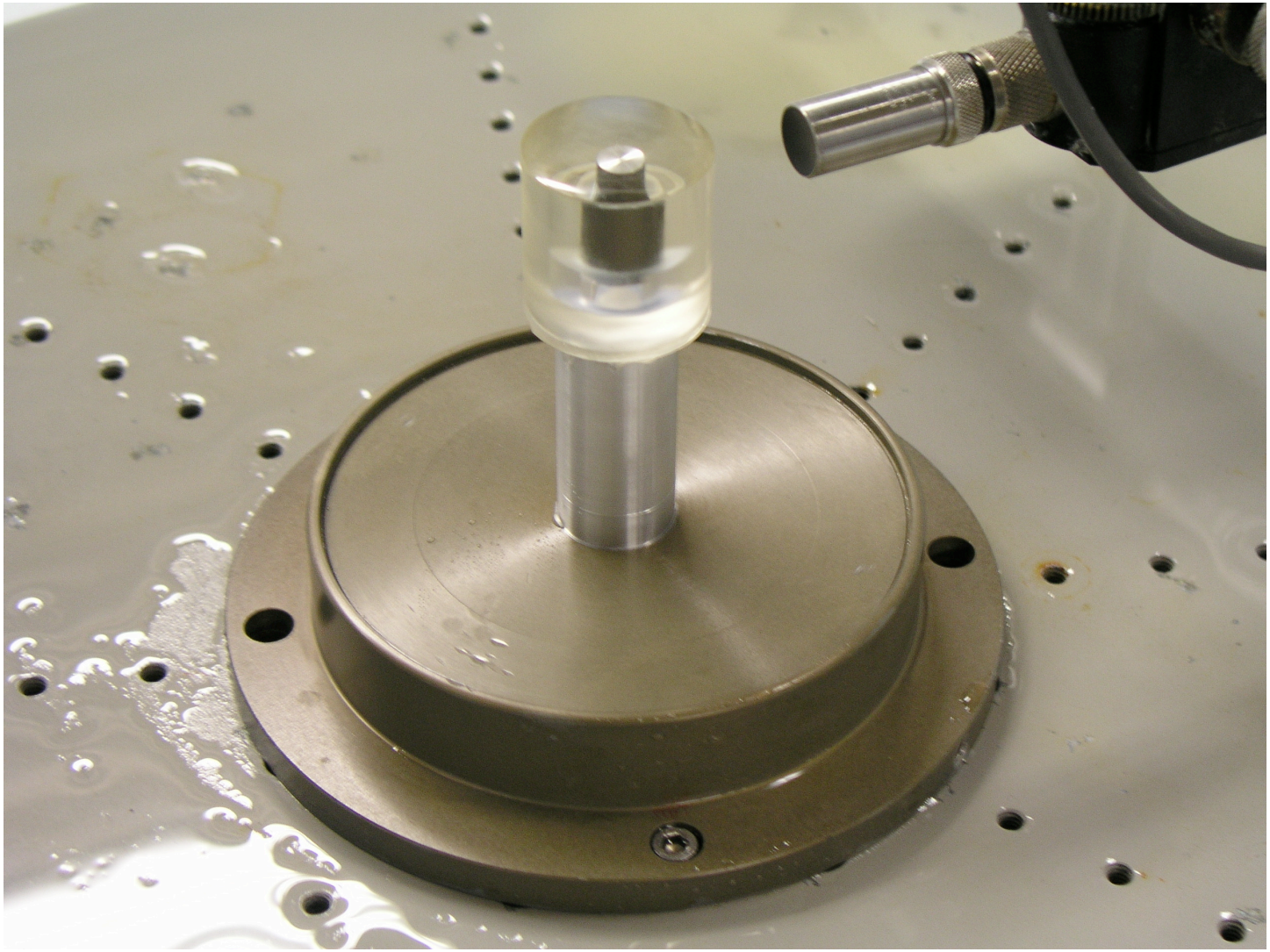
- **Problem Definition:**
  - **Ultrasonic NDE measurements**
  - **The spatial resolution problem**

- **Impulse Response Estimation for Enhancing Spatial Resolution**
  - **Mitigate "ringing" due to the transducer and propagation paths**

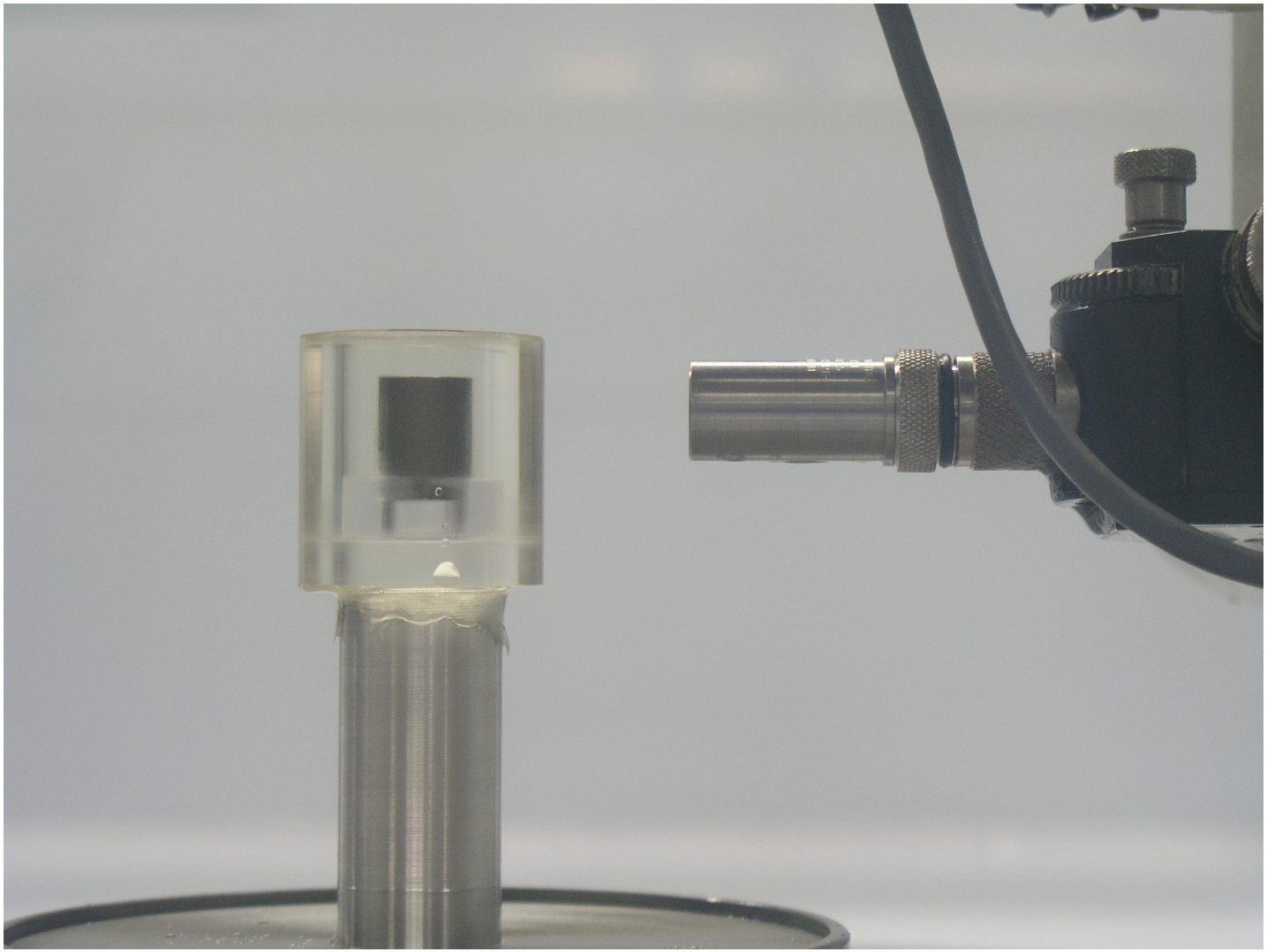
- **Workstation dedicated to processing and rendering 3D ultrasonic data sets**

- **Examples of Processing Results**

The “Phantom” Part is Placed on a Fixture And Rotated. The Transducer Position is Fixed

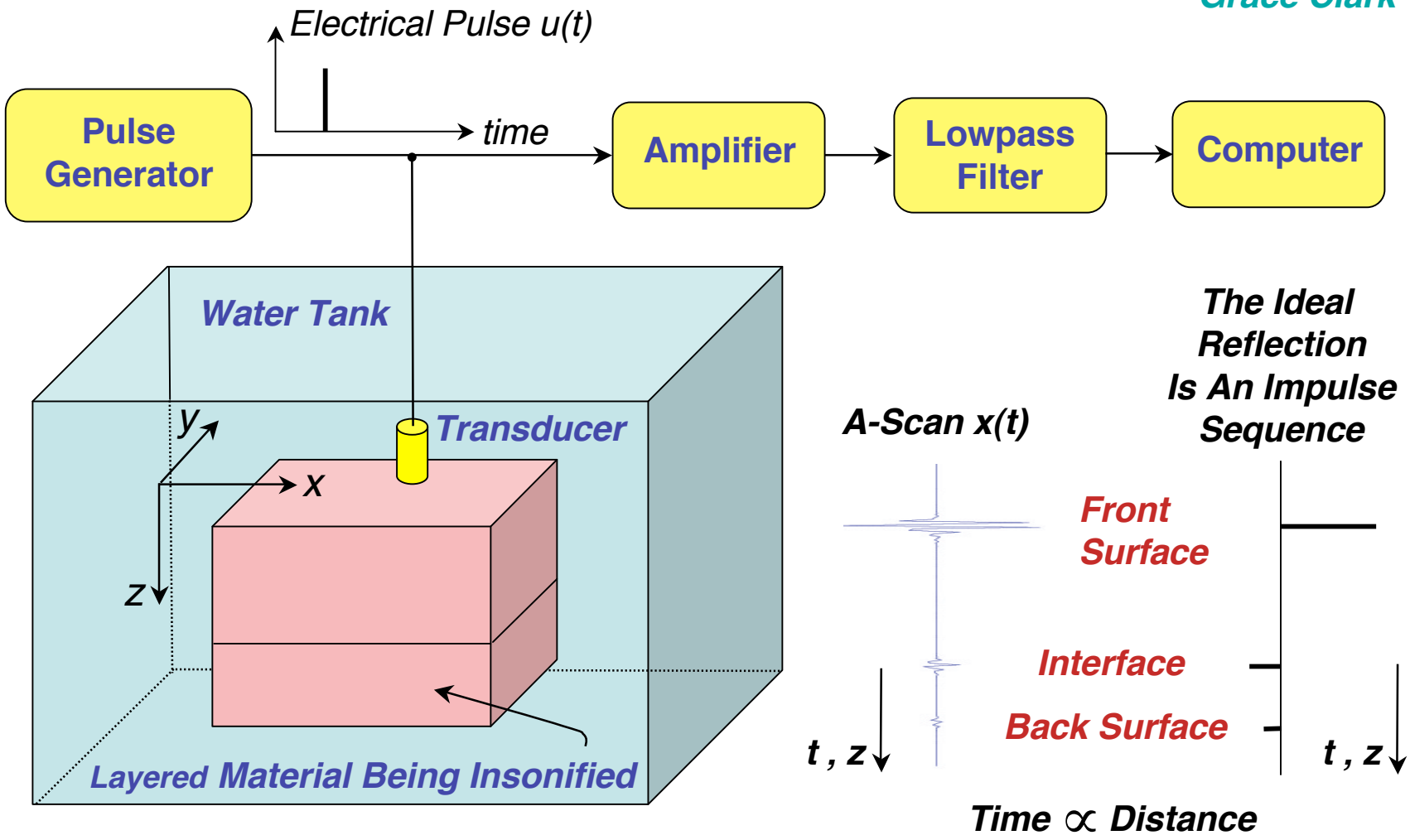


The Ultrasonic Transducer Position is Fixed As the "Phantom" Part is Rotated on the Fixture

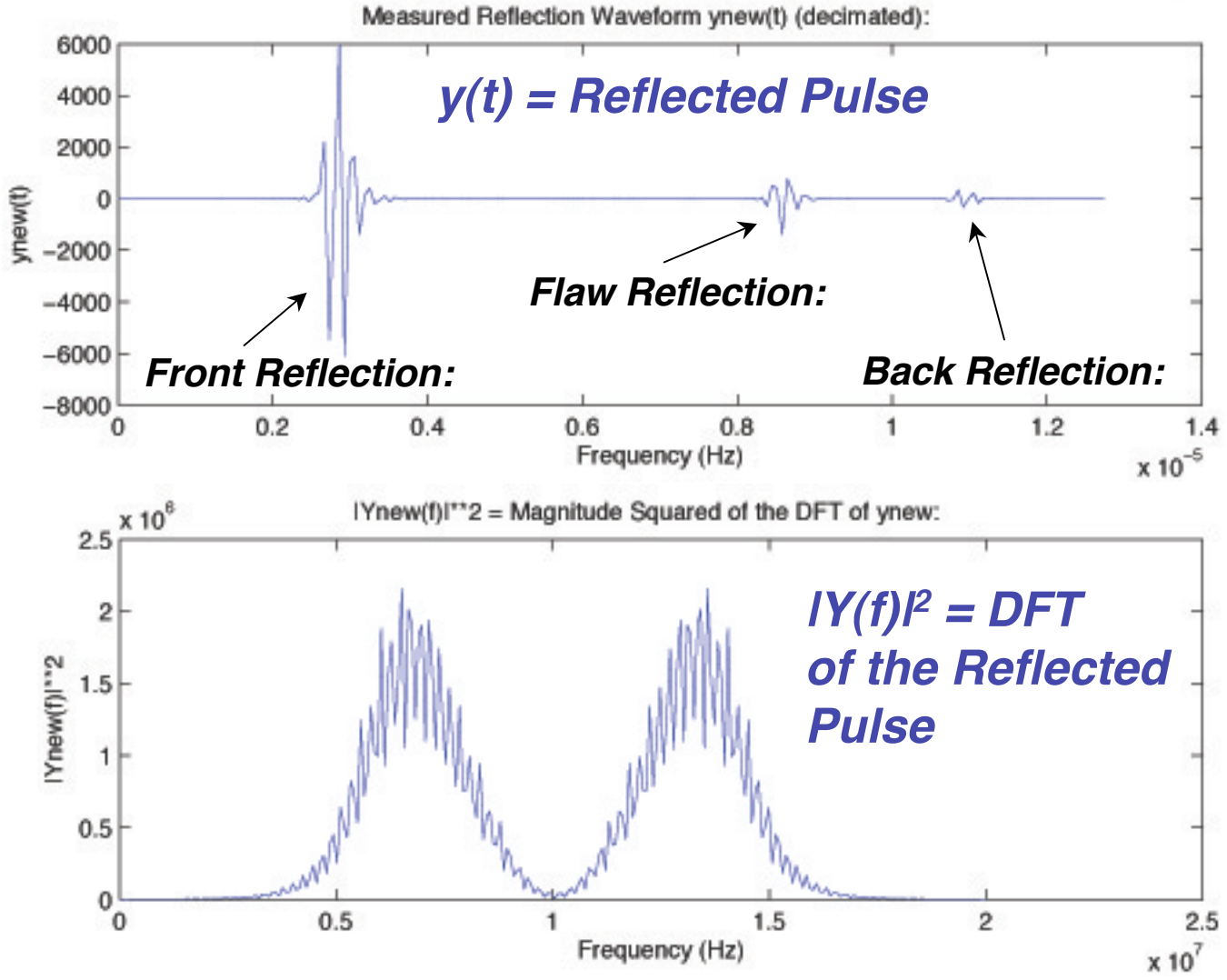


Ultrasonic Pulse-Echo Signals *(A-Scans)* Are *Distorted* By the *Transducer* and the *Propagation Paths ("Ringing")*

Grace Clark

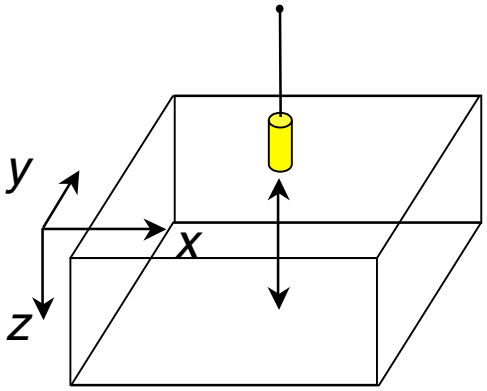


Ultrasonic Pulses Are *Bandlimited* by the Transducer ==> The Pulses *"Ring"*, *Reducing Spatial Resolution*



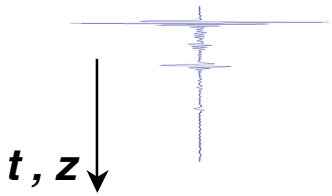
We Define Ultrasonic *A-, B-, and C-Scans* Used in Nondestructive Evaluation (NDE) Studies:

Grace Clark

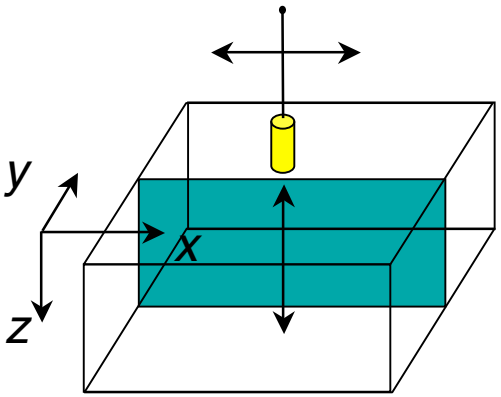


A-Scan x(t)

(A Single Waveform)

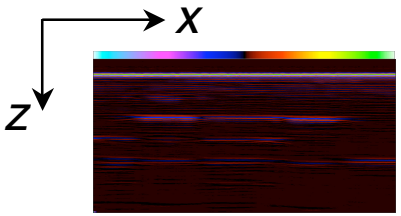


Time ∝ Distance



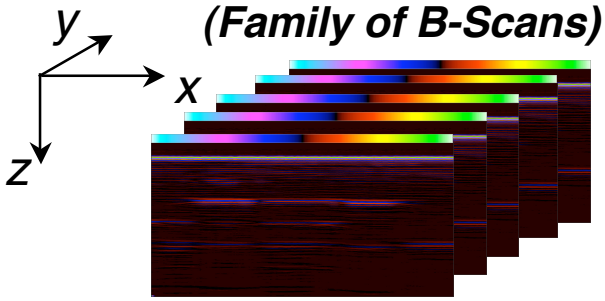
B-Scan

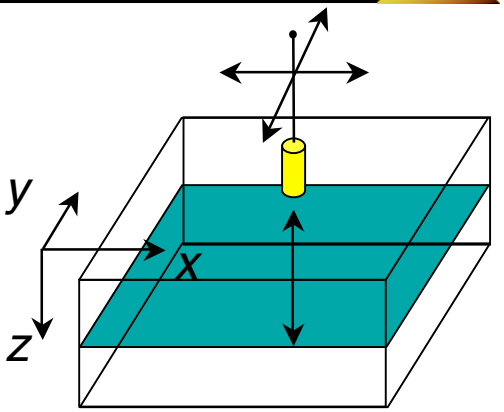
(Family of A-Scans)



3D Volume

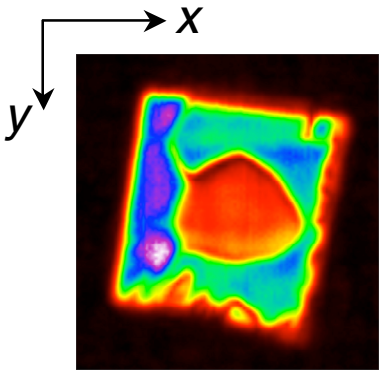
(Family of B-Scans)



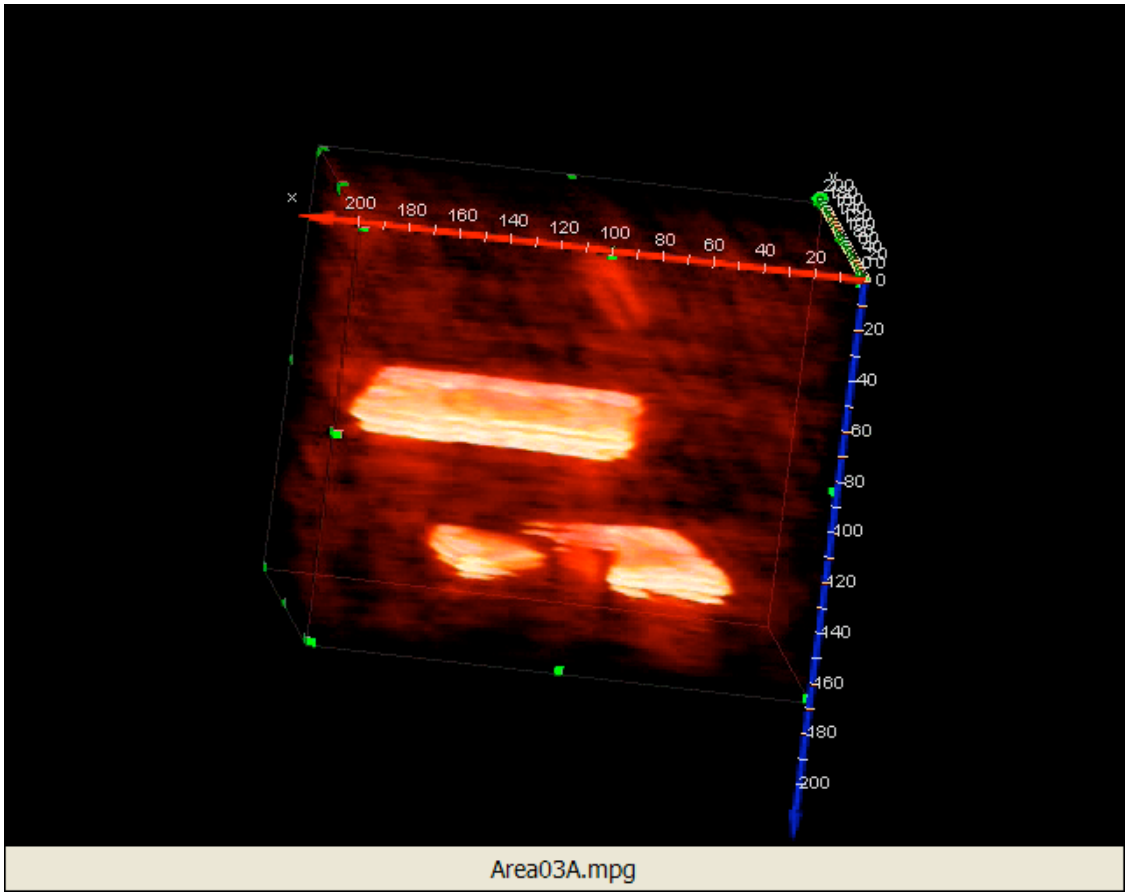


C-Scan

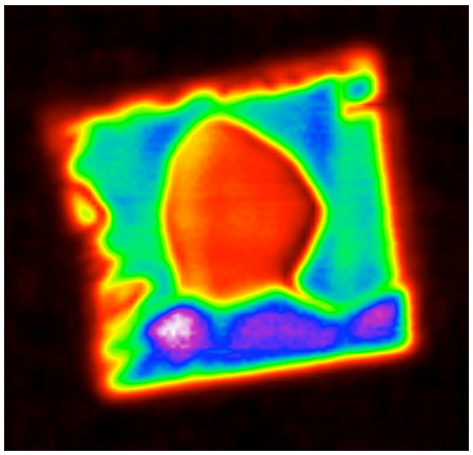
(Horizontal Slice At Depth z: Use A Time Gate)



Three Dimensional Rendering Helps Visualize the Locations of Defects/Flaws



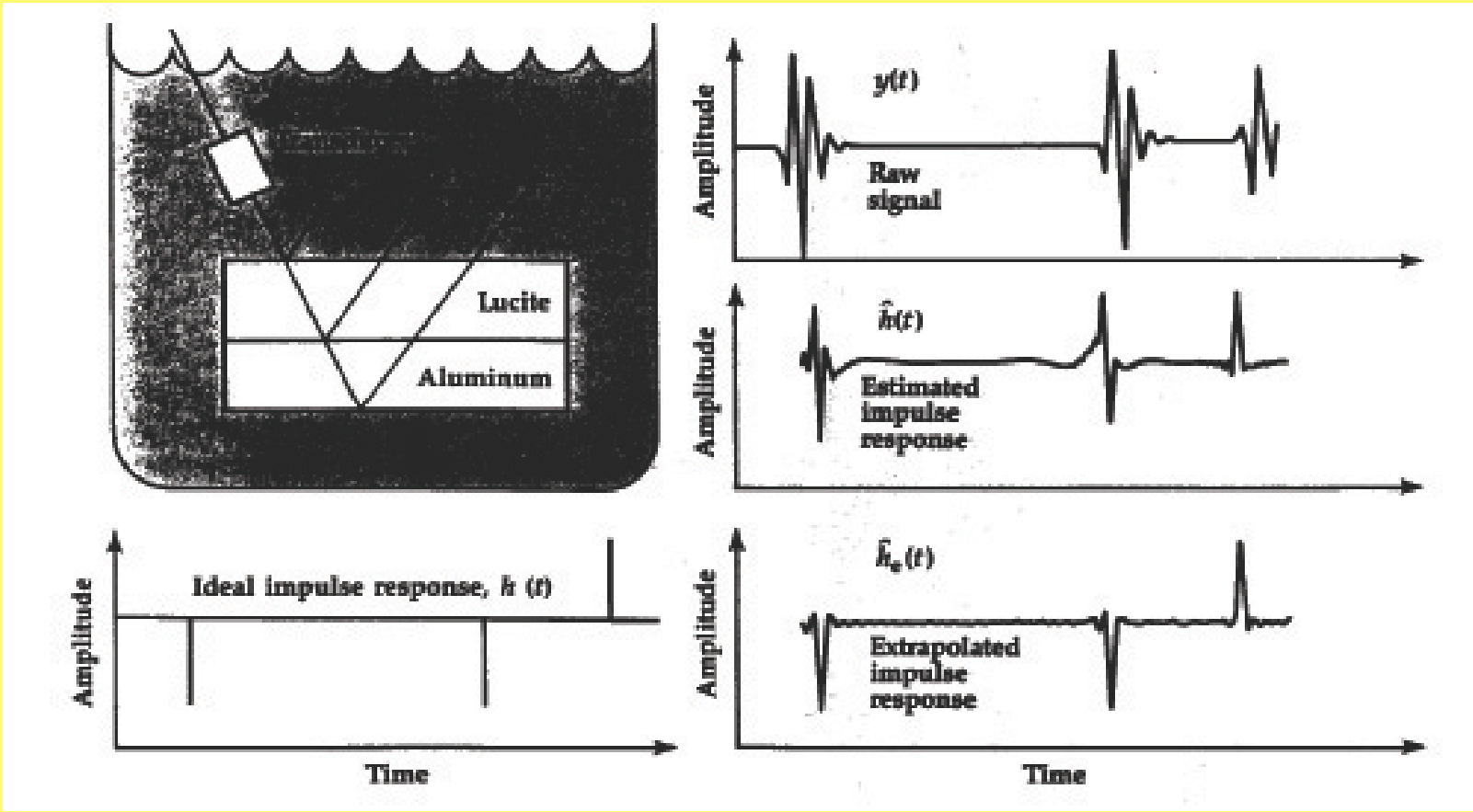
3D Volume Rendered Image
(12mm Defect in Carbon Composite Test Plate)



Original 2D C-Scan image

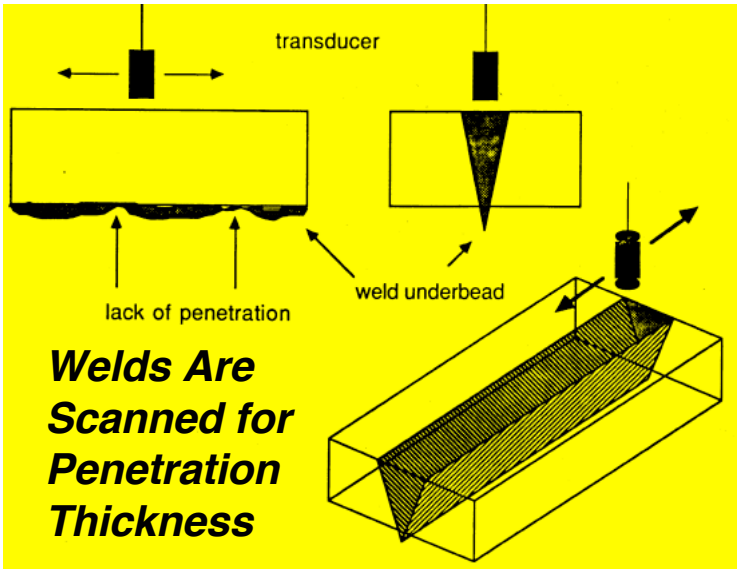
Ultrasonic Pulse-Echo Signals Are Distorted by the Transducer and the Propagation Paths

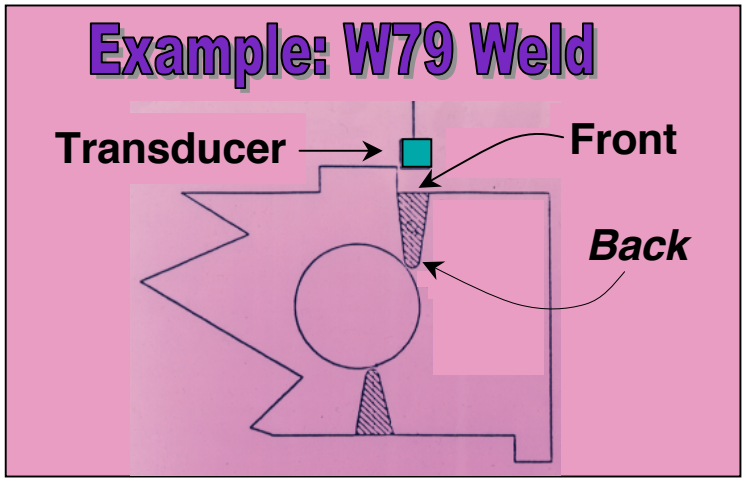
Grace Clark

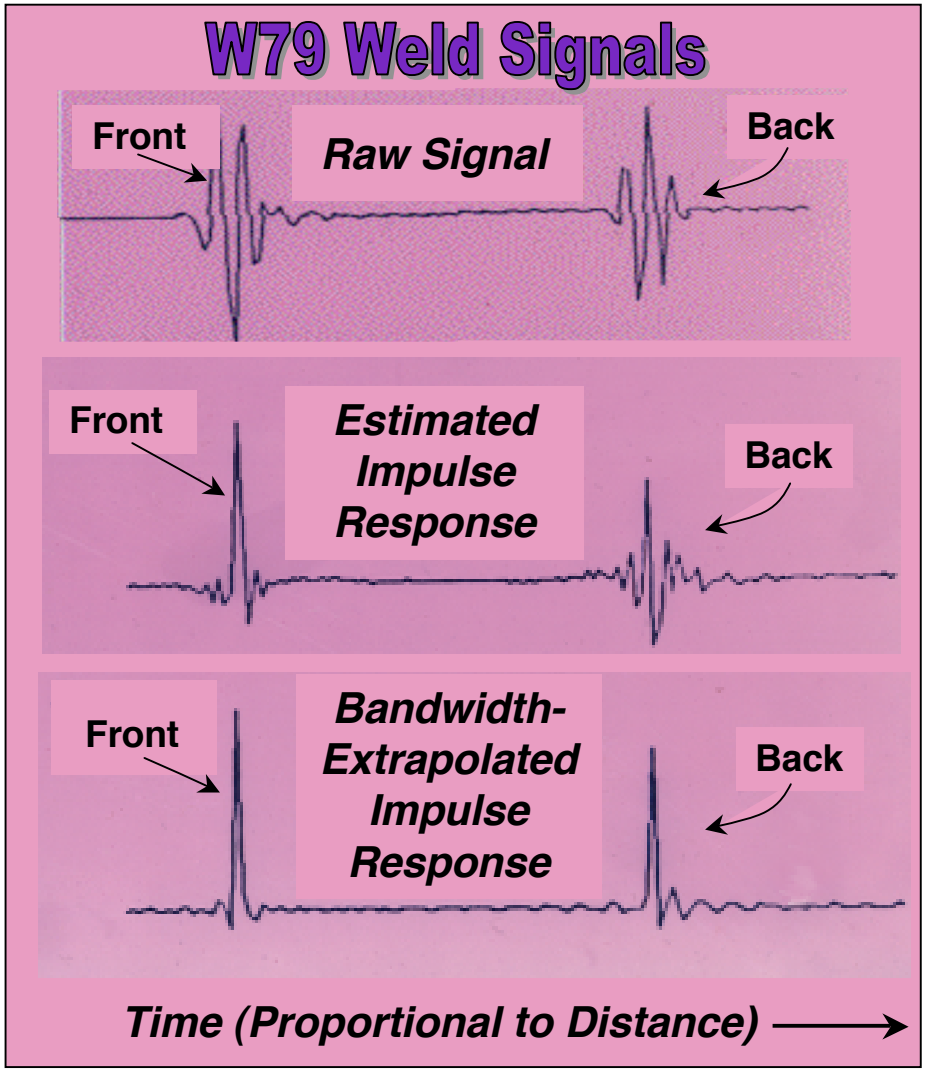


Ultrasonic Pulse-Echo Signals Are Distorted by the Transducer and the Propagation Paths

Grace Clark

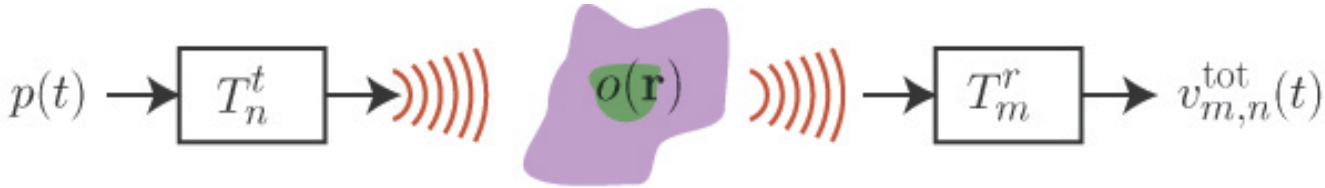






The Overall Measurement System Transfer Function:
When An Object is Present

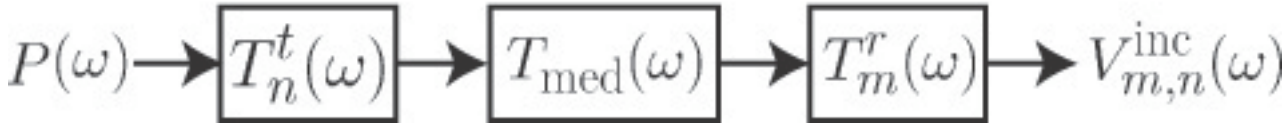
The Object Measurement Contains Information About the Transducers, the Propagation Paths, AND the OBJECT of Interest



$$P(\omega) \rightarrow T_n^t(\omega) \rightarrow T_{\text{med}}(\omega) \rightarrow H_{\text{obj}}(\omega) \rightarrow T_{\text{med}}(\omega) \rightarrow T_m^r(\omega) \rightarrow V_{m,n}^{\text{tot}}(\omega)$$

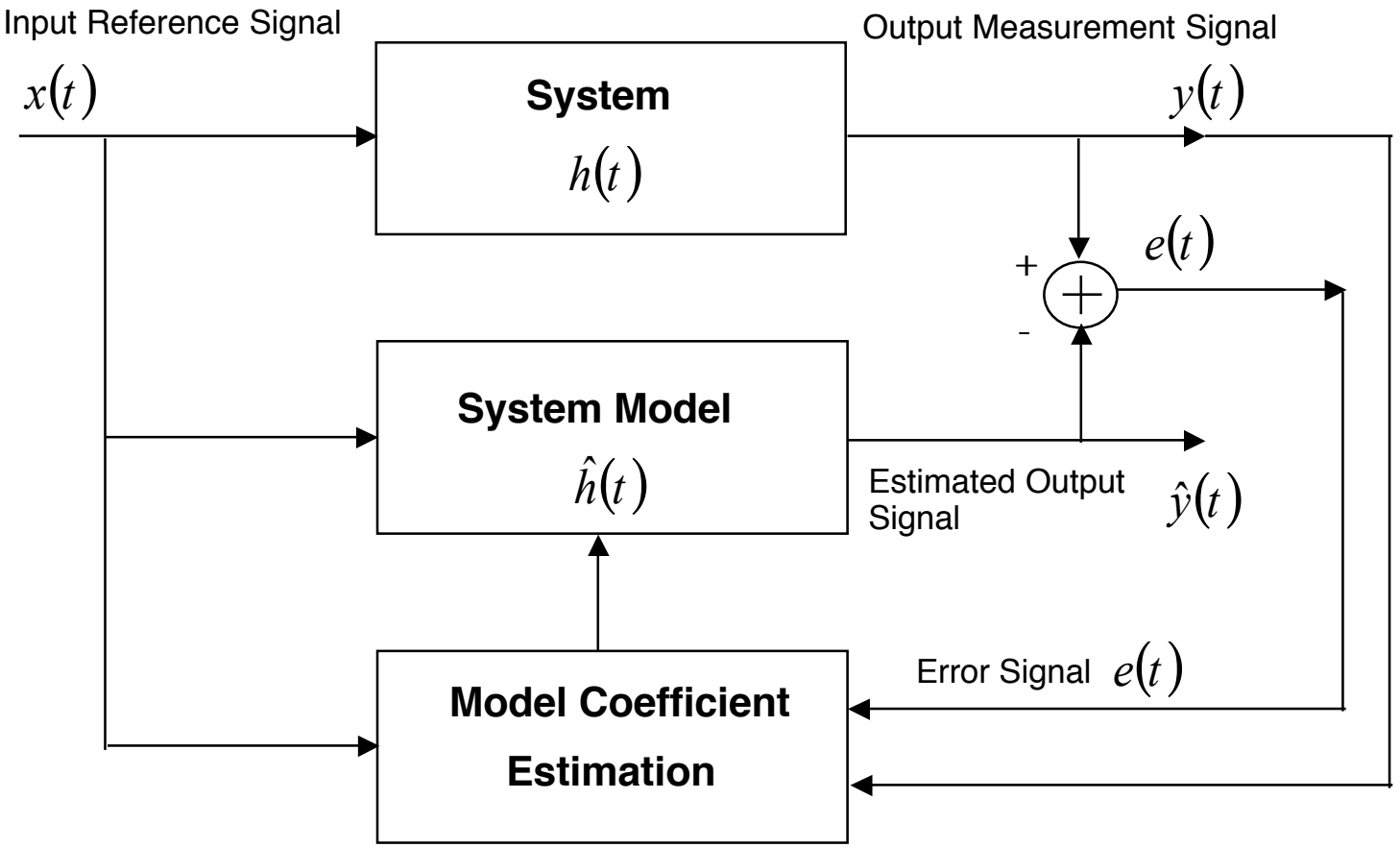
The Overall Measurement System Transfer Function:
When No Object is Present: Use This for a Reference!

The Reference Measurement Contains Information About the Transducers and the Propagation Paths
(Example: Use a Front or Back Surface Reflection)

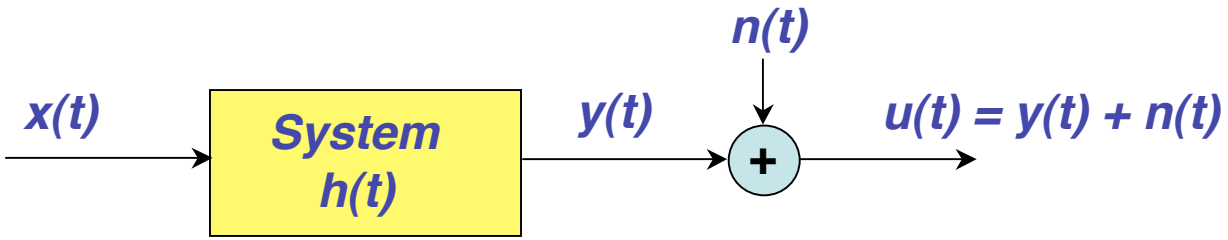


System Identification: Given Input x(t) and Output y(t), Estimate the System Impulse Response h(t)

Grace Clark



The System Identification Problem (Inverse Problem) is *Ill-Posed*



System Identification:

Given: x(t) and u(t) ==> Find: h(t)

Deconvolution:

Given: u(t) and h(t) ==> Find: x(t)

NOISE: Small perturbations in u(t) map to large differences in the estimates of h(t)

FINITE SUPPORT: When x(t) is frequency bandlimited, many operators h(t) will produce the same output u(t)

The Inverse Problem Is Very Difficult

⇒ *We Must Regularize the Problem*

- **Ill-Posed (Infinite Number of possible solutions)**
- **Bandlimited Transducer Spectral Response**
- **Ill-Conditioned - Numerical Errors Due to Spectral Zeros**

Use a (Nonparametric) Finite Impulse Response (FIR) Model for the Discrete-Time Linear, Shift-Invariant System

$$\mathbf{u} = \mathbf{y} + \mathbf{n} \qquad \mathbf{n} \text{ is Stationary WGN } \sim N\left[0, \sigma^2 I\right]$$

where $\mathbf{y} = \mathbf{X}\mathbf{h}$ ***(Convolution)***

M = Number of Impulse Response Model Coefficients
N = Number of Input Samples in the Record

$$\begin{bmatrix} y(0) \\ y(1) \\ \vdots \\ y(N-1) \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} x(0) & 0 & 0 & 0 \\ x(1) & x(0) & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots \\ x(N-1) & x(N-2) & \cdots & x(0) & x(0) \\ 0 & x(N-1) & & x(1) & x(0) \\ \vdots & \vdots & & \vdots & \vdots \\ 0 & 0 & & x(N-1) & x(N-2) \\ 0 & 0 & & 0 & x(N-1) \end{bmatrix} \begin{bmatrix} h(0) \\ h(1) \\ \vdots \\ h(M-1) \end{bmatrix}$$

(M + N-1 X 1) ***(M+N-1) X M*** ***(M X 1)***

Minimizing the Sum-Squared Error Subject to An Energy Constraint Gives the Estimate:

If we minimize the sum-squared error subject to the condition $\hat{\mathbf{h}}^{\mathrm{T}}\mathbf{h} < C$, an energy constraint on $\hat{\mathbf{h}}$, then the form of the estimate is:

$$\hat{\mathbf{h}}(\alpha) = \left[\hat{\mathbf{R}}_{\mathbf{xx}} + \alpha\mathbf{I}\right]^{-1}\hat{\mathbf{r}}_{\mathbf{xu}}$$

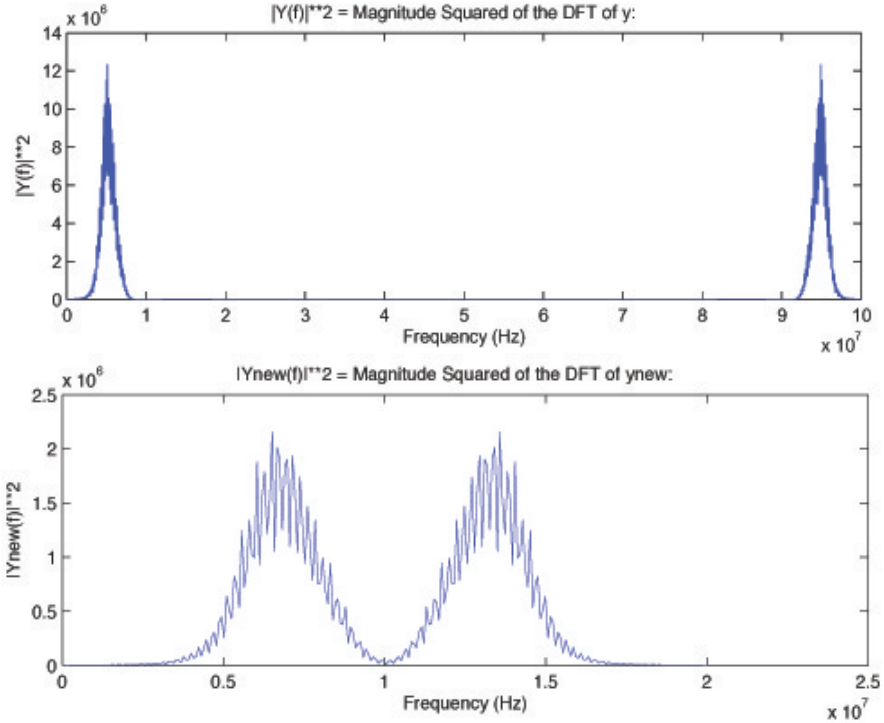
Where:

- α is a nonlinear, monotonically decreasing function of C and $\hat{\mathbf{h}}(\alpha)$
- $\hat{\mathbf{h}}(\alpha)$ is a ***BIASED*** estimate of $\mathbf{h}$
  Biased in the sense that the Fourier transform of $\hat{\mathbf{h}}(\alpha)$ is forced To be small at frequencies where x(k) has little energy.

We Face a Bias vs. Variance Tradeoff!!

We *Preprocess* the Signals to Enforce Algorithmic Assumptions and to Minimize Artifacts in the Solution

- Ensemble average multiple signals to reduce noise variance.
- Remove means and trends (caused by instrumentation) to ensure linearity.
- Align signals temporally to ensure causality.
- Lowpass filter and decimate (down-sample) by a factor of M to remove spectral zeros (help improve the condition number of $\hat{\mathbf{R}}_{xx}$).



Raw Spectrum (Oversampled)

Lowpass Filtered and Decimated Spectrum (M = 13/2)

The Workstation Provides a Central Location for Processing and Displaying 3-D Ultrasonic Data

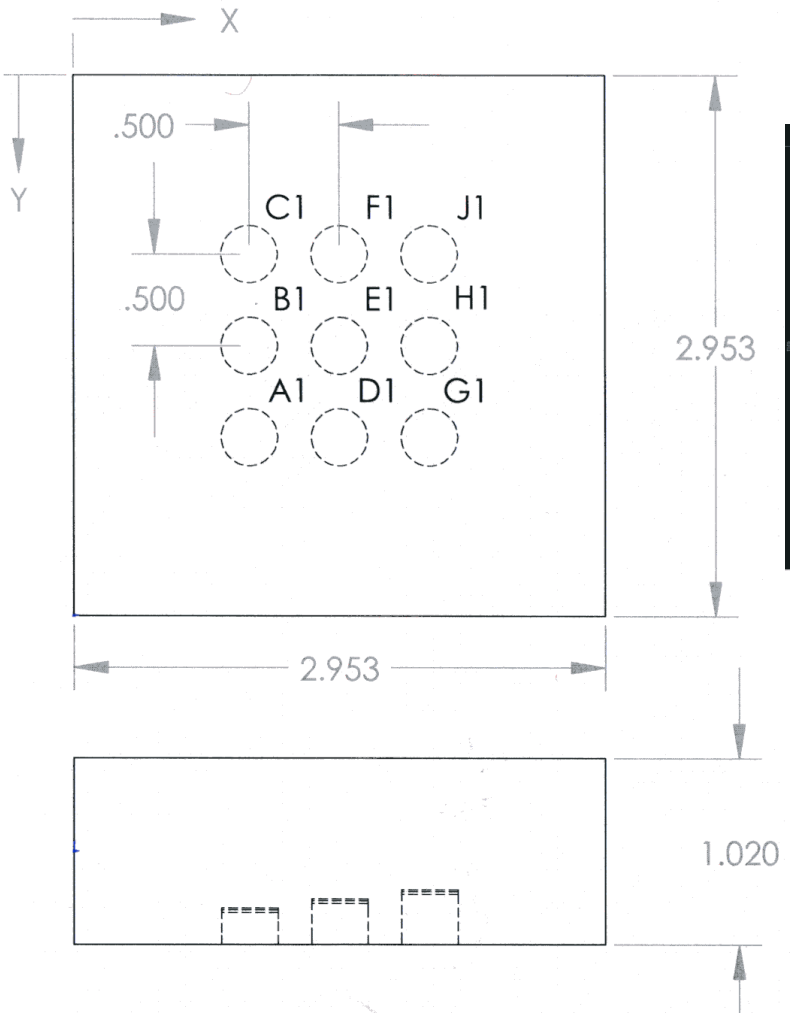
3-D Rendering Computer

3-D Processing Computer

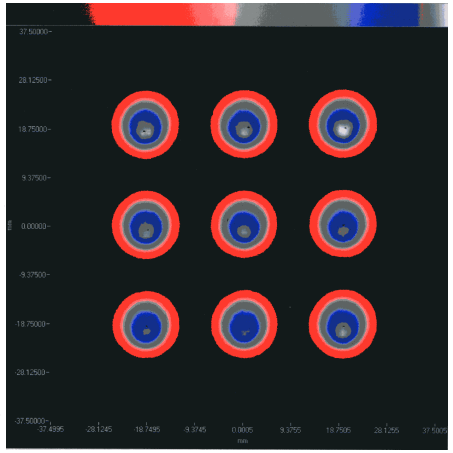
We Developed a User Interface Connecting NI-CVI and Matlab

- The Interactive user interface provides…
  - — Support for multiple file formats
    - LLNL Acoustic Microscope
    - Panametrics Scanning Systems
  - — Display of volume data
    - C-Scan, B-Scan, A-Scan
  - — Interactive selection of input signal used for signal processing
  - — Signal processing parameter setup
    - Linked to base volume file
  - — Software connection between NI-CVI and MatLab
  - — Display of processed volume data set

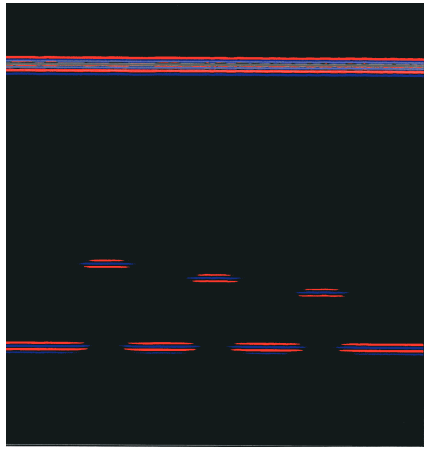
We Constructed a "Phantom" Part - *Aluminum Block* Containing *Flat-Bottom Holes*

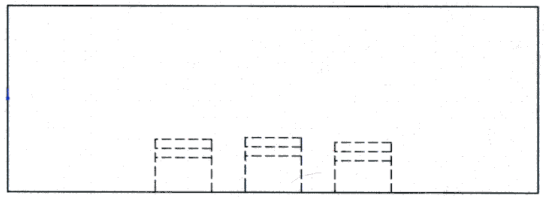


C-Scan Image (Horizontal Slice)



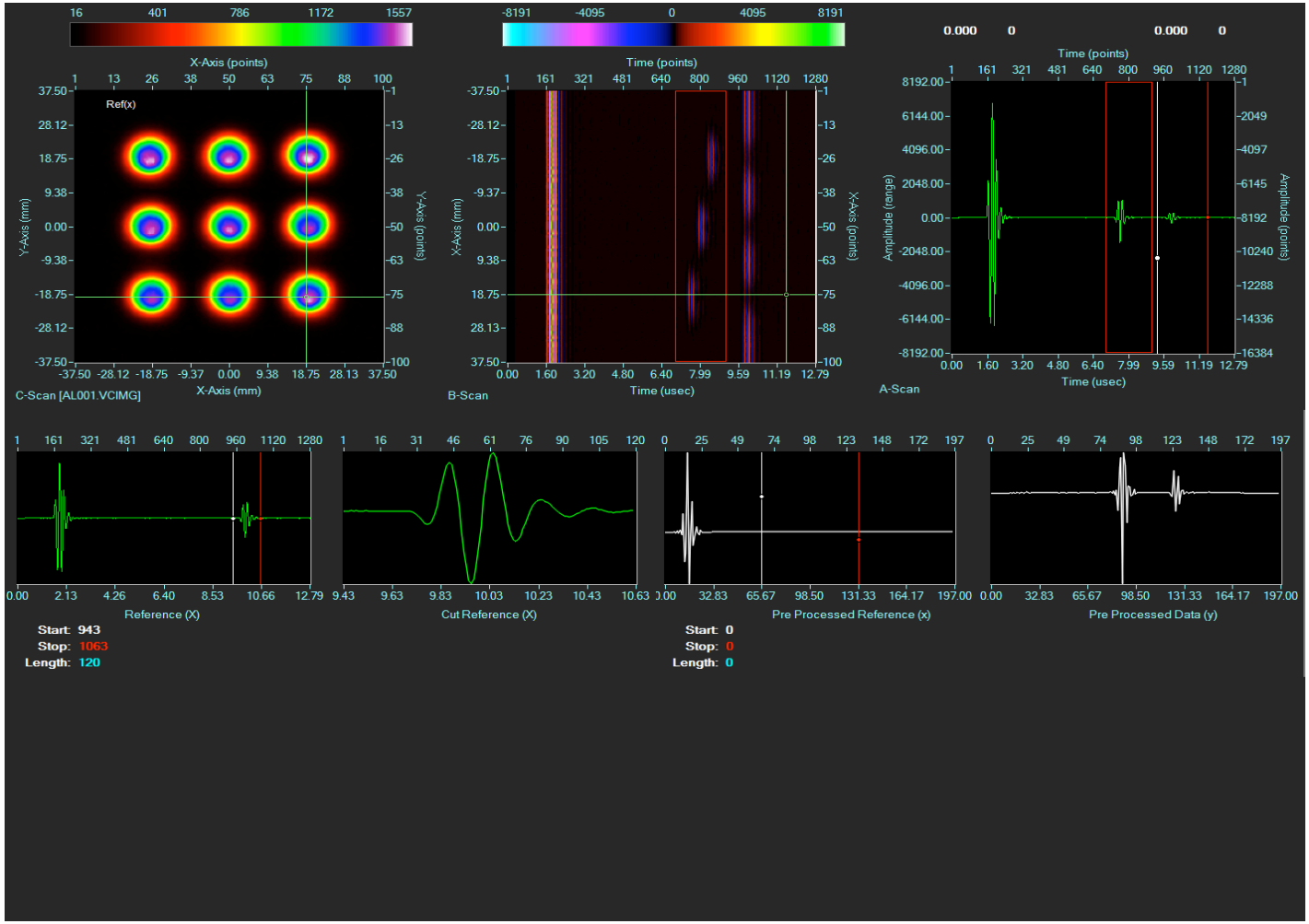
B-Scan Image (Vertical Slice)





User Interface Provides a Visual Tool for Fine Tuning Algorithm Parameters and Processing

National Instruments CVI user interface linked to MATLAB



Measured Signals x(t), y(t) and y(t-delta)
Reference Signal = Front Reflection

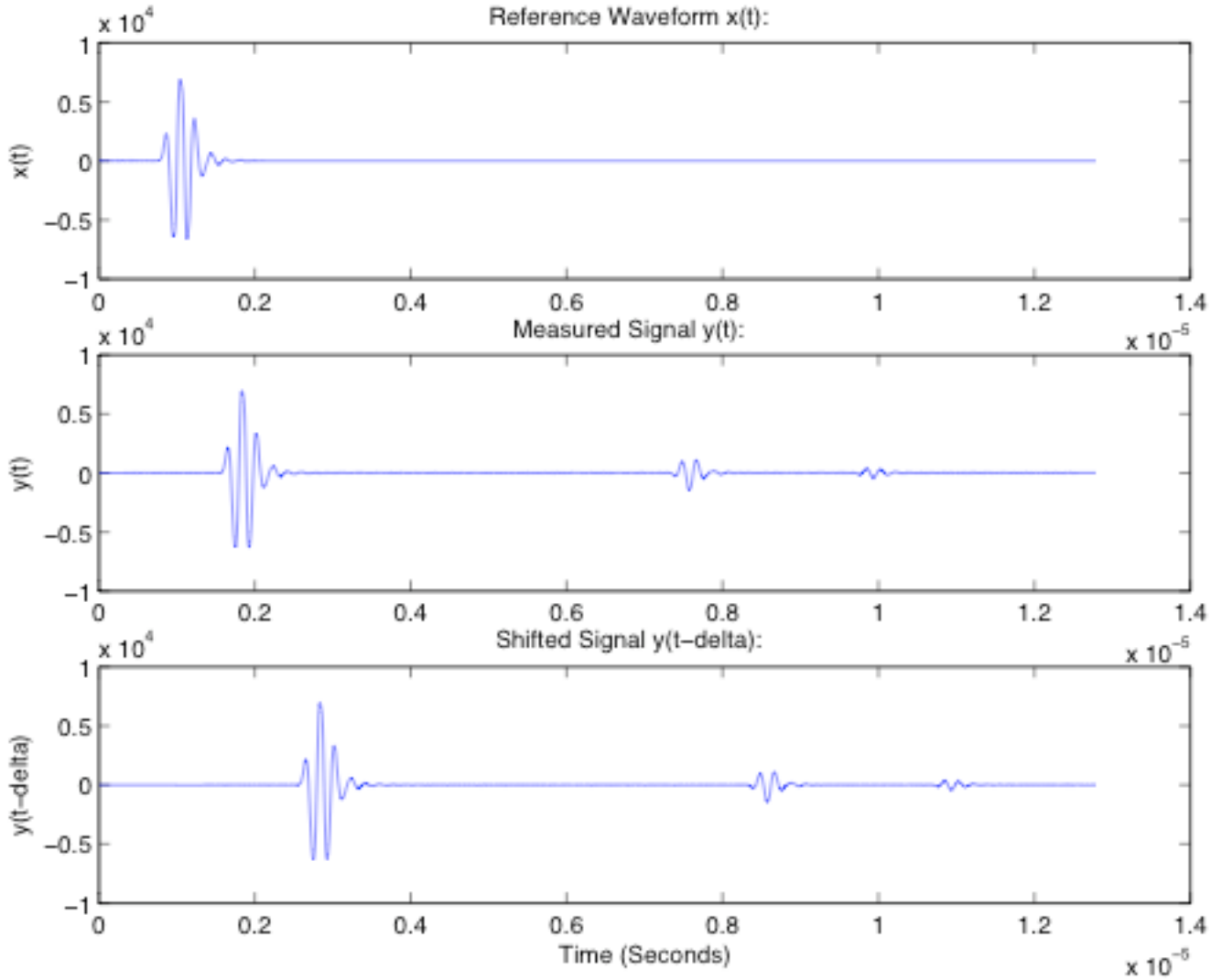


Figure 4.0.pdf: Estimated Impulse Response

Reference Signal = Front Reflection

We Are Primarily Interested in the *Hole Reflection*

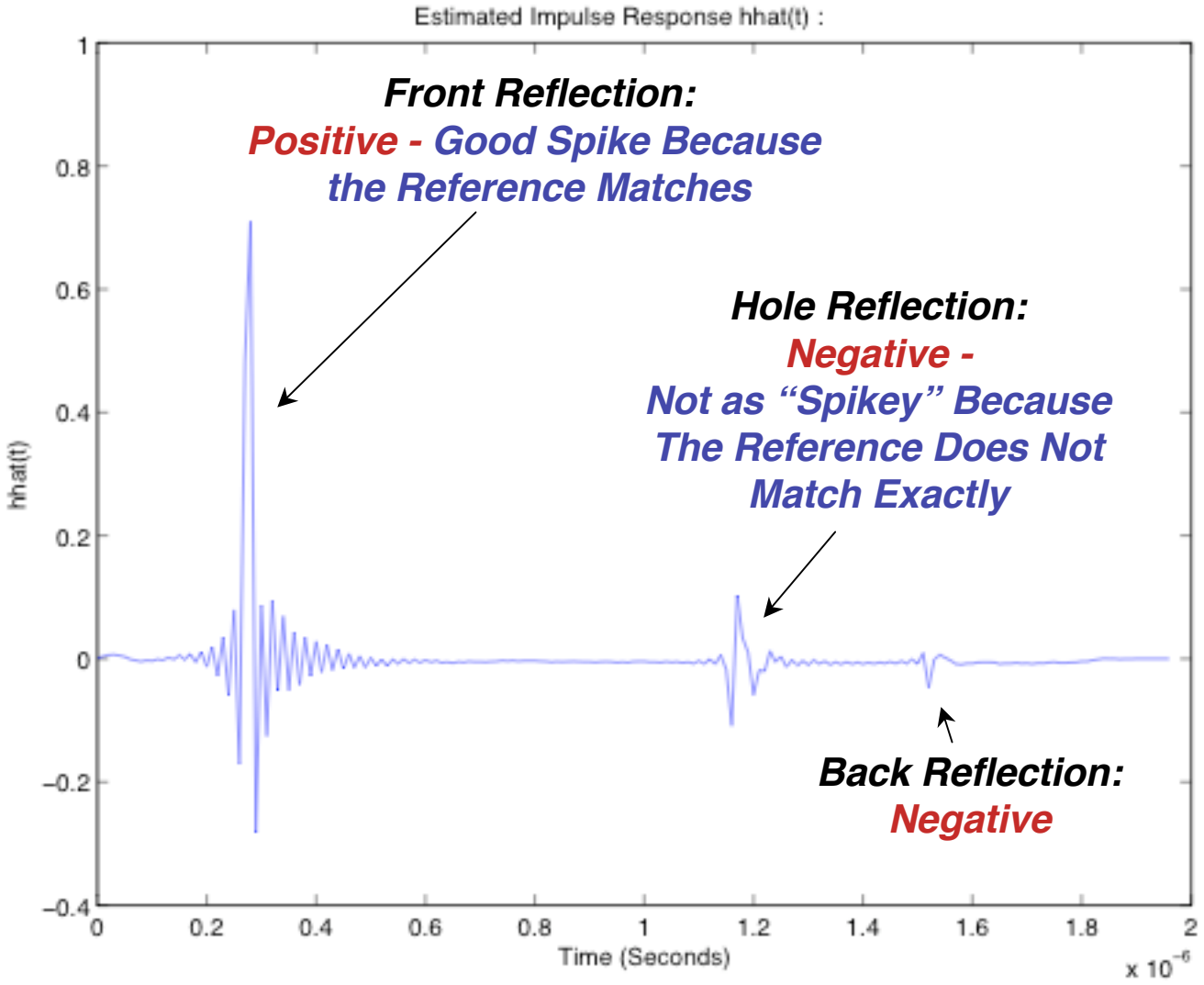


Figure 6.2.pdf: Measured Signals
Reference Signal = Back Wall Reflection

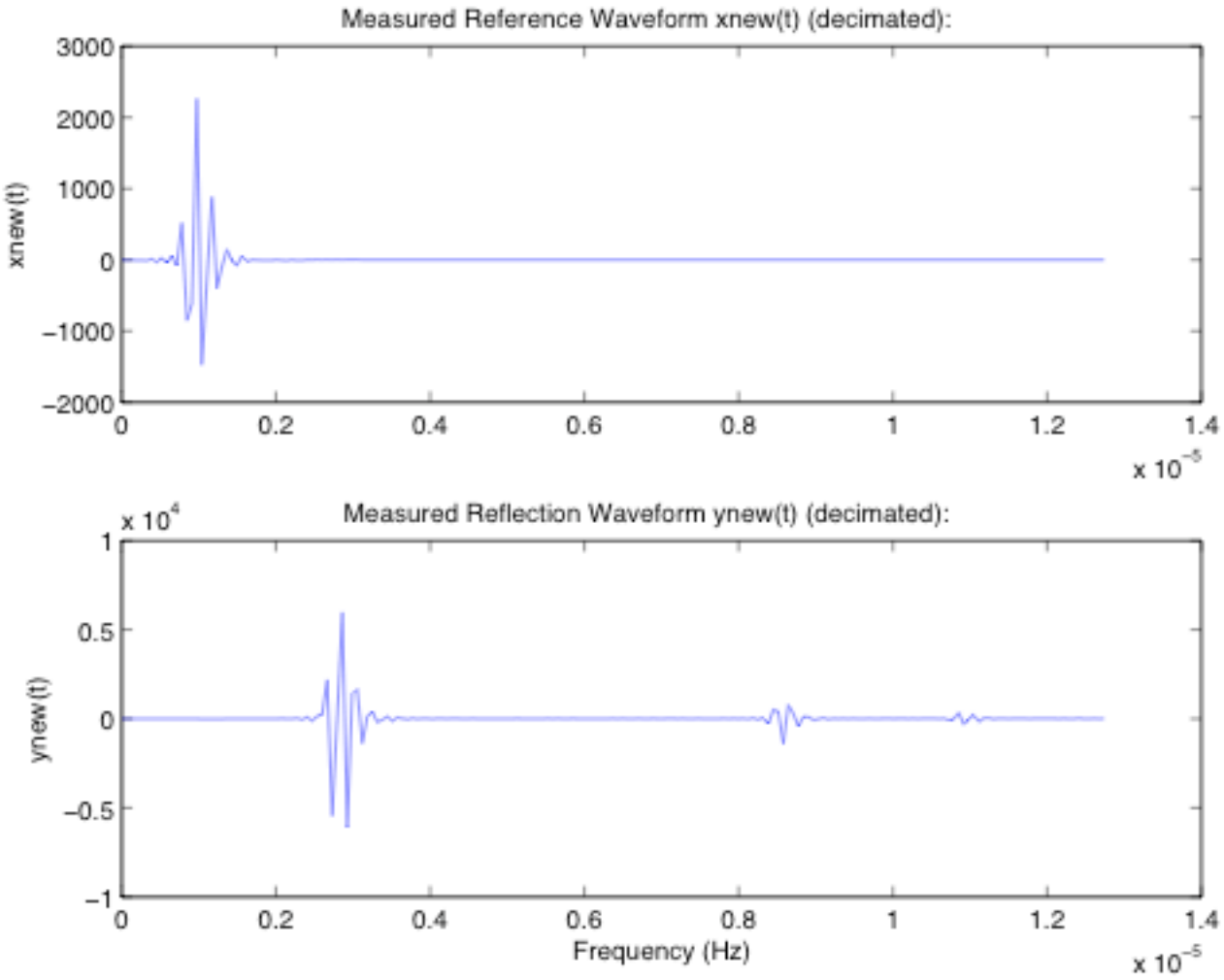
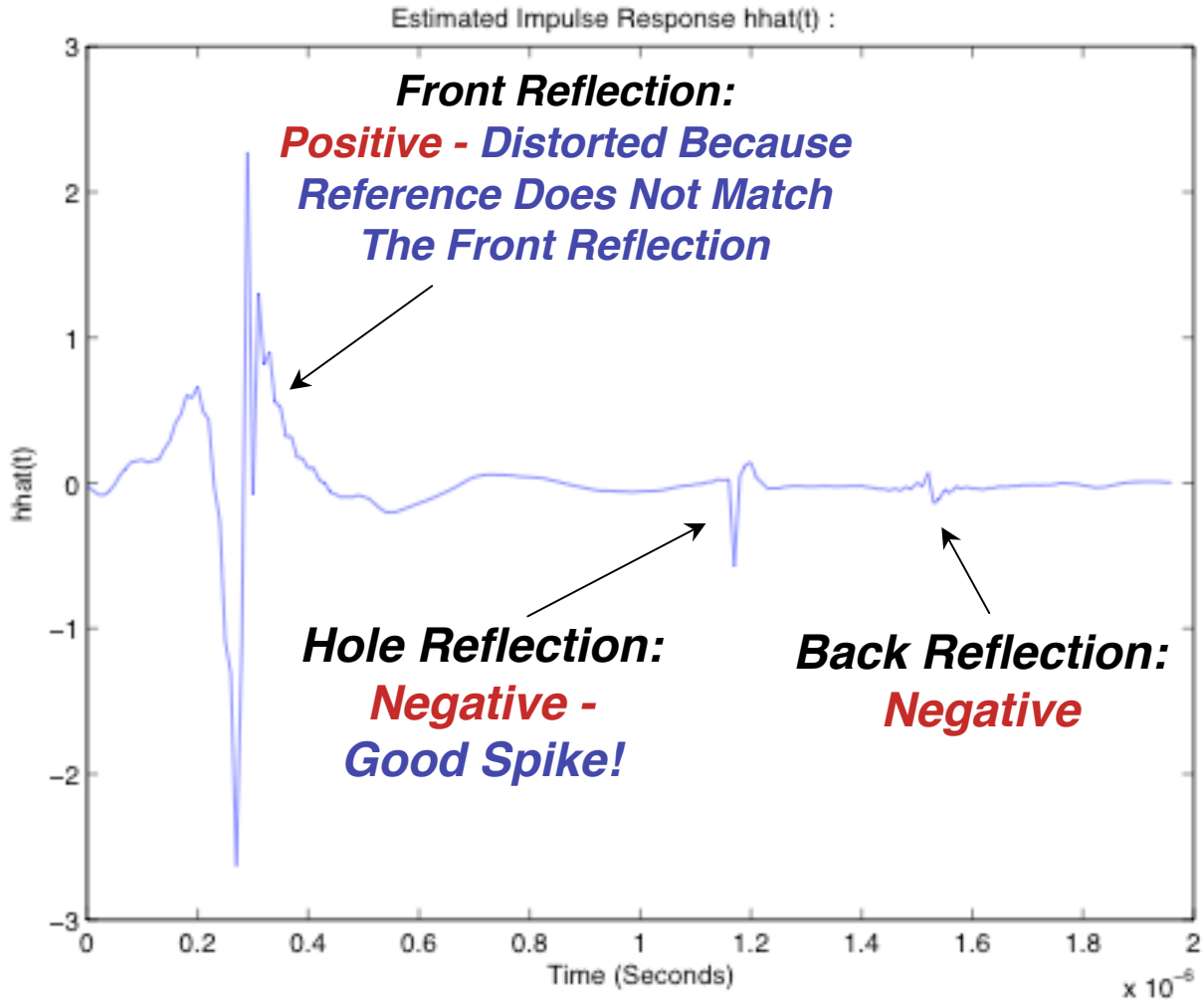


Figure 6.4.pdf: Estimated Impulse Response

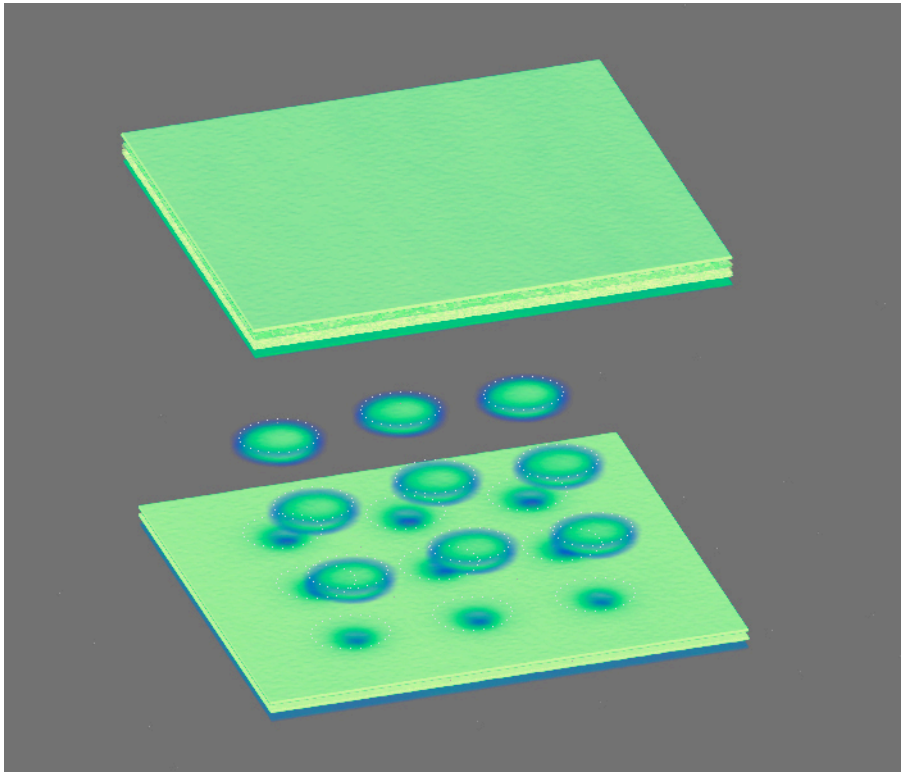
Reference Signal = Back Reflection

We Are Primarily Interested in the *Hole Reflection*

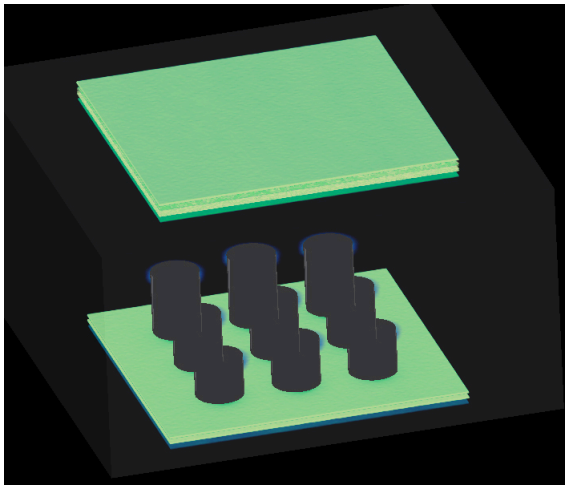


We Can Combine CAD Models With 3-D Data To Clarify Ultrasonic Evaluation Results

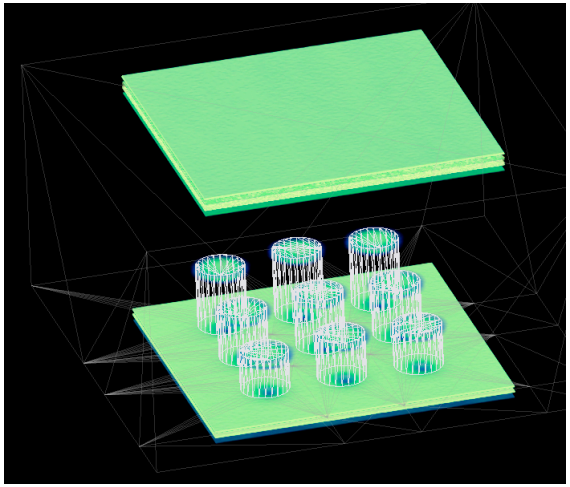
3-D Ultrasonic Data Det



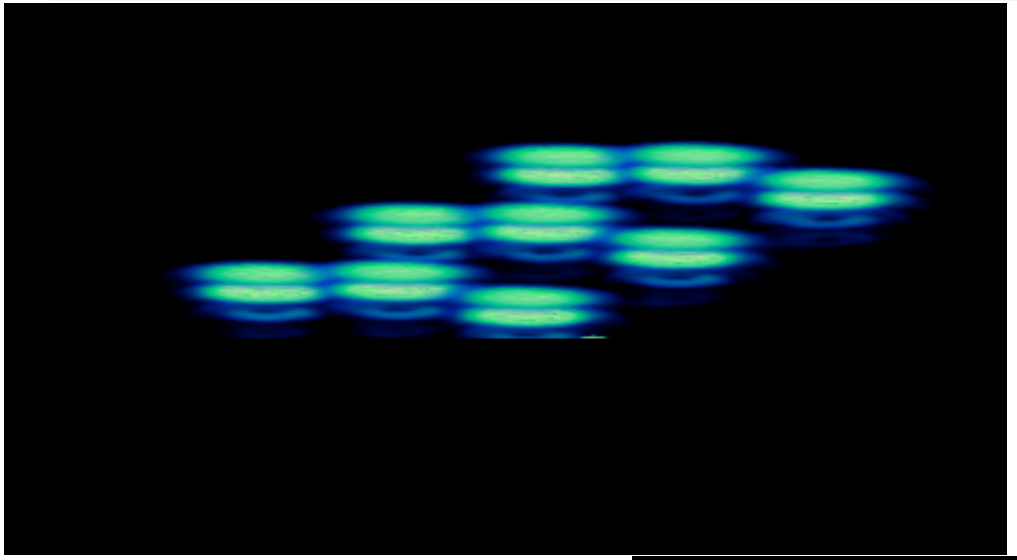
3-D data and CAD Model-*Solid*



3-D data and CAD Model-*Lines*

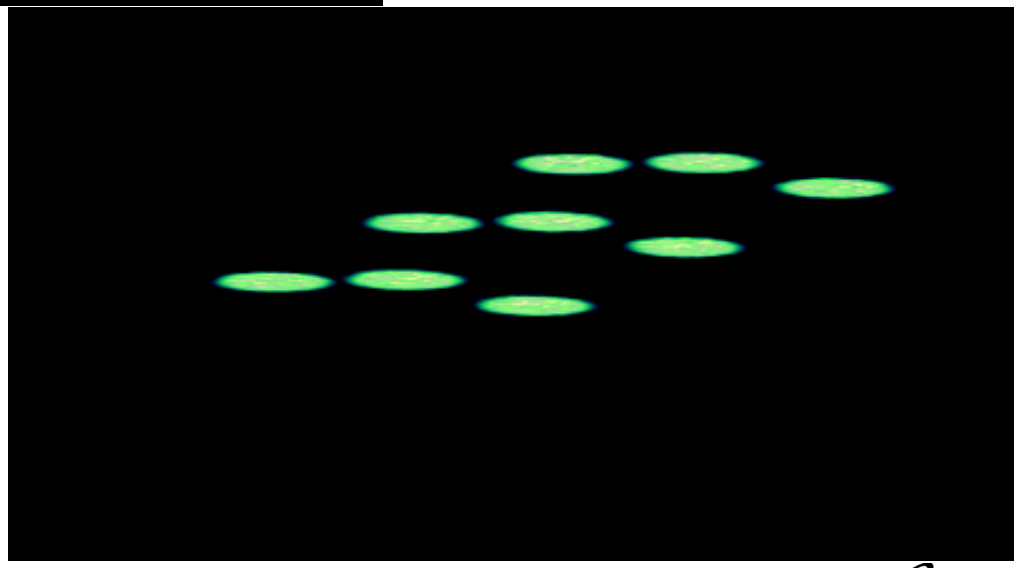


The Processed 3D Volume Shows Greatly-Enhanced Spatial Resolution



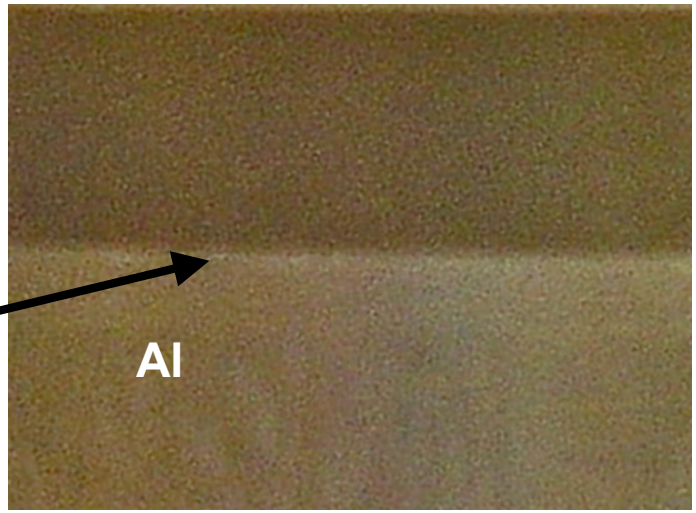
Raw 3D Volume

Processed 3D Volume

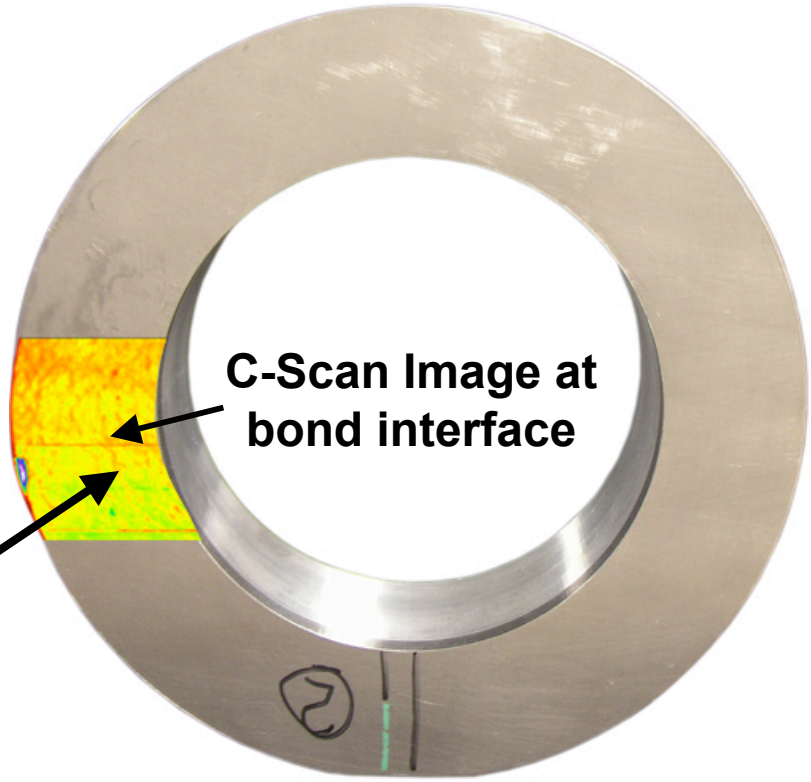


Niobium-aluminum Explosive Bond for Flight Test (JTA)

Cross Section (Photo)

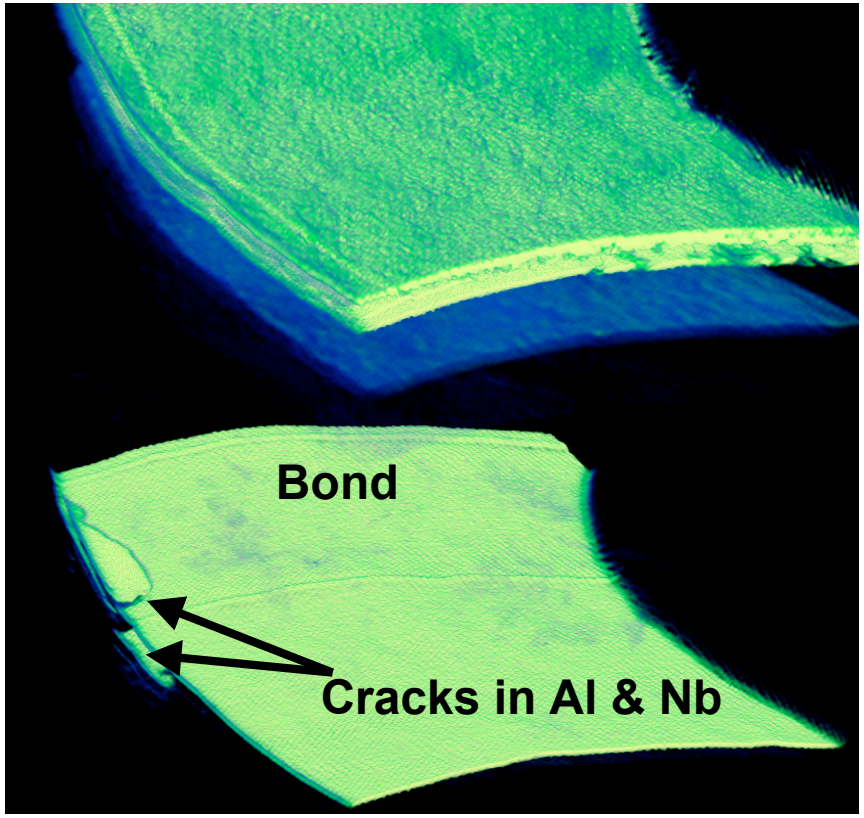


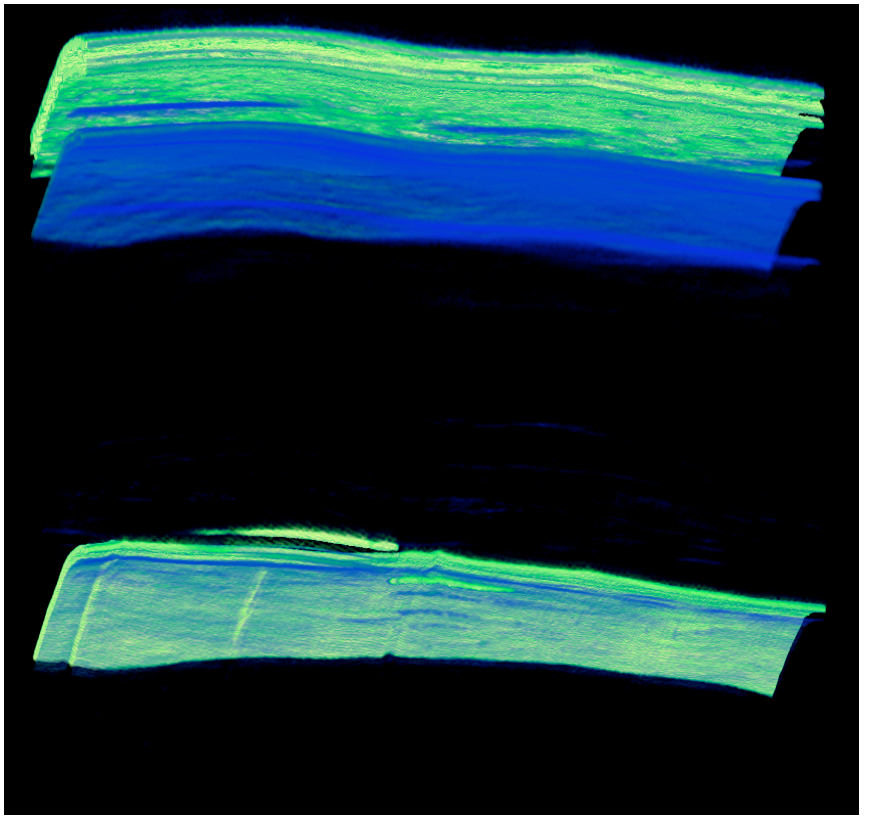
Plan View (Photo)



Conventional ultrasonic imaging revealed an indication at the Nb-Al interface

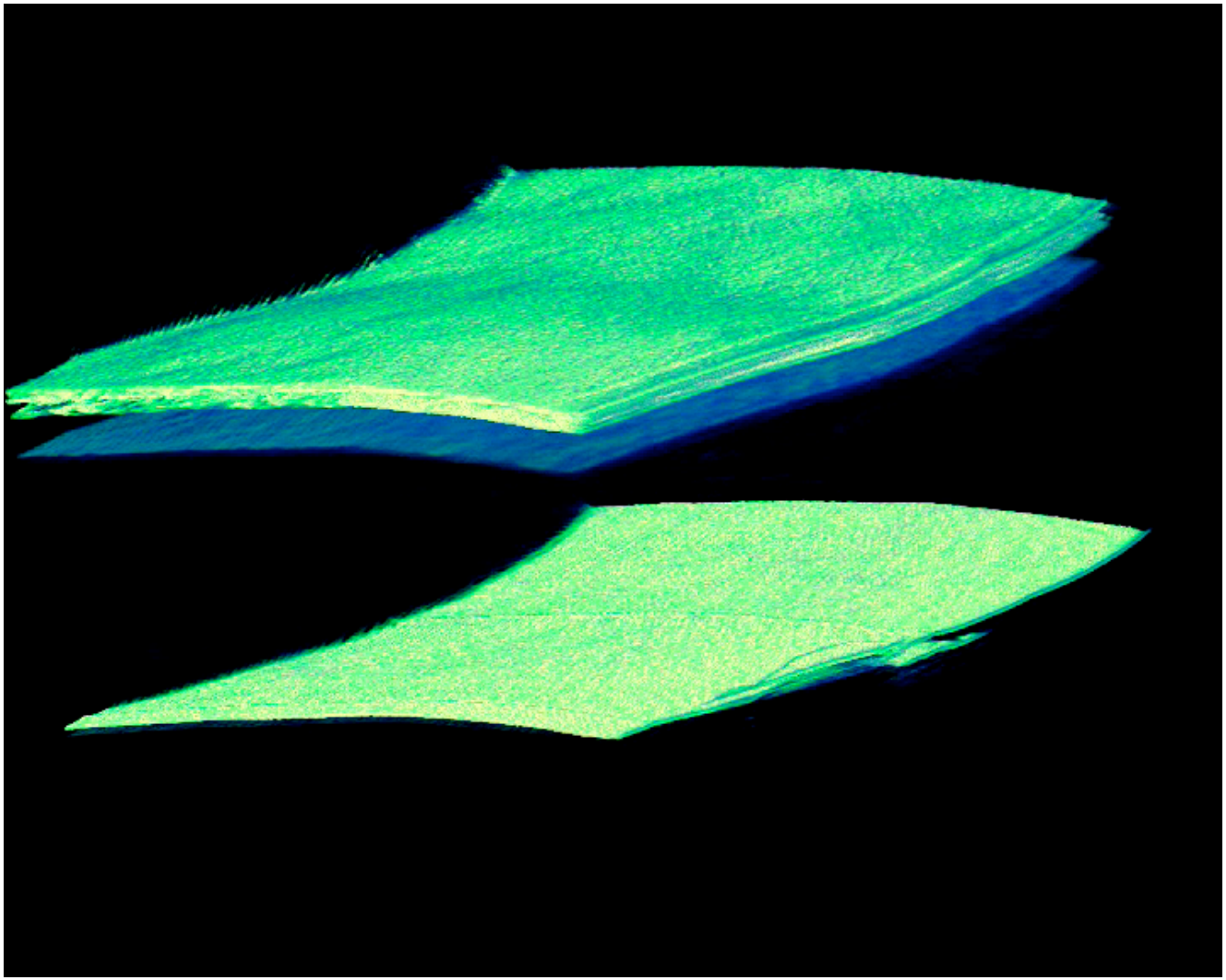
Three Dimensional Rendering Reveals That the Indication Is Multiple Cracks Adjacent to Nb-al Bond Interface





Knowledge of Damage to the Base Material Is Valuable For the Development Process

Three Dimensional Rendering Reveals Multiple Cracks Adjacent to Nb-Al Bond Interface



Future Work, Conclusions

- We have in place:
  - Ultrasonic test bed
  - Workstation and interactive software dedicated to 3D ultrasonic image processing and rendering
  - We can combine CAD drawings with rendered data for image analysis/comparison
  - System Identification algorithms/software for enhancing spatial resolution

- Future Work
  - Techbase project for super-resolution algorithm implementation (research is complete)
  - Integrate the super-resolution algorithm with the workstation system
  - Applications to programmatic data sets